XXXII International Workshop on High Energy Physics (HPSI)

Presentation on

Properties of doubly heavy Baryons

by

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Review of The Standard Model

Particle Physics is the study of:

- MATTER: the fundamental constituents of the universe- the elementary particles
- FORCE: the fundamental forces of nature, i.e. the interactions between the elementary particles

Review of The Standard Model

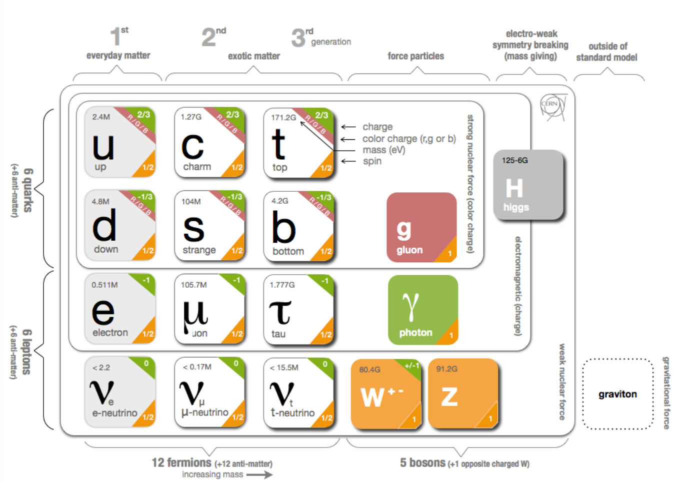
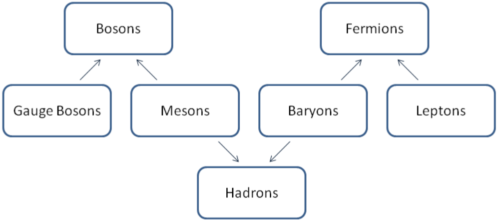


Figure: The Standard model [http://united-states.cern]

Review of The Standard Model



Baryons

- Light sector
- Light-Heavy Sector
- Heavy Sector

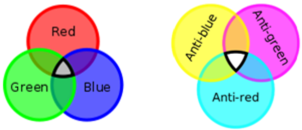
Mesons

- Light sector
- Heavy-Light Sector
- Heavy Sector

Exotic States

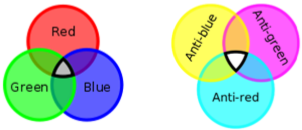
- Glueballs
- Tetraquarks
- Pentaquarks
- Hexaquarks

QCD: the theory of the strong interaction



- The interaction is governed by massless spin 1 objects called gluons.
- Quarks inside the hadrons exchange gluons and create a very strong color force field. To conserve color charge, quarks constantly change their color by exchanging gluons with other quarks.

QCD: the theory of the strong interaction



- The interaction is governed by massless spin 1 objects called gluons.
- Quarks inside the hadrons exchange gluons and create a very strong color force field. To conserve color charge, quarks constantly change their color by exchanging gluons with other quarks.
- As the quarks within a hadron get closer together, the force of containment gets weaker so that it asymptotically approaches zero for close confinement. The quarks in close confinement are completely free to move about. This condition is referred to as "asymptotic freedom".
- Confinement: Energy required to produce a separation of one of the quarks out, far exceeds the pair production energy of a quark-antiquark pair, it can create a jet of mesons as the energy imparted to the quark is used to produce quark-antiquark pairs.

An essential requirements for the progress in hadronic physics is the full usage of present facilities and development of new ones, with a clear focous on experiments that provide geniune insight into the inner workings of QCD.

Many review articles are describing the various properties of Hadrons and Exotics particles. They also mentioed their possibilities and quantum numbers.
Some are,

- E. Klempt, J.M. Richard, Rev. Mod. Phys. 82, 1095 (2010)
- V. Crede and W. Roberts, Rept. Prog. Phys., 76: 076301 (2013)
- N. P. Samios et al., Rev. Mod. Phys., 46: 49 (1974)
- A. Valcarce et al., Rept. Prog. Phys., 68: 965 (2005)
- M. M. Giannini, E. Santopinto, Chin. J. Phys., 53: 020301 (2015).
- J. Sonnenschein, D. Weissman, (2018) *arXiv: 1812.01619[hep-ex]*
- Jean-Marc Richard et al., arXiv:1910.08295v1(2019)
- Ke-Wei Wei et al., Phys. Rev. D 95, 116005 (2017)

Spectroscopy of heavy flavor hadrons has attracted considerable interest in recent years due to the many experimental facilities.

- CLEO
- BaBar and Belle
- Tevatron
- Selex
- CERN: LHCb
- Future experiments PANDA, Belle-II

The search for light resonances is the main focus of the baryon programs at

- JLab
- Mainzer Mikrotron (MAMI)
- the Beijing Spectrometer (BES)
- the Electron Stretcher and Accelerator (ELSA) facility (the Crystal Barrel collaboration)
- GRAAL
- the Two Arms Photon Spectrometer (TAPS)
- SAPHIR and CLAS.
- we can expect new results from analysis projects such as EBAC, Julich, SAID, and MAID.

Different Approaches

The excited states of the nucleon have been studied experimentally since the 1950's. They contributed to the discovery of the quark model in 1964 by Gell-Mann, and Zweig , and were critical for the discovery of "color" degrees of freedom as introduced by Greenberg .

Excited Doubly heavy baryon masses: Theoretical study

Approach	Authors
relativistic quark model	Ebert et al.
variational approach	Roberts et al.
Fadeev approach	Valcarce et al.
Lattice QCD	Padmanath et al., Brown et al.,Paula et al.
Hamiltonian Model	T. Yoshida et al.
Regge phenomenology	K-Wei Wei et al.
Sum rules	K. Azizi et al.,Hua-Xing Chen et al;Aliev et al.
diquark picture	Qi-Fang LÃij et al.
Chiral Quark Model	Li-Ye Xiao et al.

We used The Hypercentral Constituent Quark Model(hCQM), which was first introduced by M. Ferrariset al., in 1995.

The Hypercentral Constituent Quark Model

The relevant degrees of freedom for the relative motion of the three constituent quarks are provided by the relative Jacobi coordinates ($\vec{\rho}$ and $\vec{\lambda}$) which are given by

$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r_1} - \vec{r_2}) \qquad \vec{\lambda} = \frac{m_1\vec{r_1} + m_2\vec{r_2} - (m_1+m_2)\vec{r_3}}{\sqrt{m_1^2 + m_2^2 + (m_1+m_2)^2}} \tag{1}$$

The confining three-body potential is chosen within a string-like picture, where the quarks are connected by gluonic strings and the potential strings increases linearly with a collective radius r_{3q}.

We define hyper radius x and hyper angle ξ in terms of the absolute values ρ and λ of the Jacobi coordinates,

$$x = \sqrt{\rho^2 + \lambda^2} \;\; and \;\; \xi = arctan\left(\frac{\rho}{\lambda}\right) \tag{2}$$

R. Bijker, F. Iachello, A. Leviatan, Annals Phys. 284, 89 (2000)
M. M. Giannini and E. Santopinto, Chin. J. Phys. **53**, 020301 (2015)
E. Santopinto, Phys. Rev. C72, 022201 (2005)

The Hypercentral Constituent Quark Model

The hyper radius x is a collective coordinate and therefore the hypercentral potential contains also the three-body effects. The Hamiltonian of three body baryonic system in the hCQM is then expressed as

$$H = \frac{P_x^2}{2m} + V(x) \tag{3}$$

where, $m = \frac{2m_\rho m_\lambda}{m_\rho + m_\lambda}$, is the reduced mass.

The hyperradial Schrodinger equation reduces to,

$$\left[\frac{-1}{2m}\frac{d^2}{dx^2} + \frac{\frac{15}{4} + \gamma(\gamma+4)}{2mx^2} + V(x)\right]\phi_\gamma(x) = E\phi_\gamma(x) \tag{4}$$

The Hypercentral Constituent Quark Model

The hypercentral potential V(x)

$$V(x) = V^0(x) + \left(\frac{1}{m_\rho} + \frac{1}{m_\lambda}\right) V^{(1)}(x) + V_{SD}(x) \tag{5}$$

$$V^{(0)}(x) = \frac{\tau}{x} + \beta x \quad \text{and} \quad V^{(1)}(x) = -C_F C_A \frac{\alpha_s^2}{4x^2} \tag{6}$$

$$\begin{aligned} V_{SD}(x) &= V_{SS}(x)(\vec{S_\rho}.\vec{S_\lambda}) + V_{\gamma S}(x)(\vec{\gamma} \cdot \vec{S}) \\ &+ V_T(x)\left[S^2 - \frac{3(\vec{S} \cdot \vec{x})(\vec{S} \cdot \vec{x})}{x^2}\right] \end{aligned} \tag{7}$$

Y. Koma *et al.* Phys. Rev. Lett **97**, 122003 (2006).
M B Voloshin, Prog. Part. Nucl. Phys. **51**, 455 (2008).

Introduction
The Model
Doubly heavy Baryons
N* and Δ baryons
Closure
References

Heavy baryons

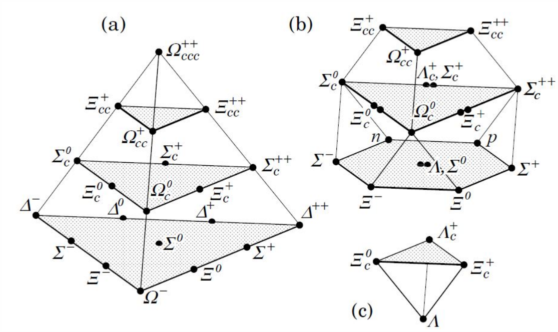


Figure: (a) The symmetric 20_s of SU(4). (b) The mixed-symmetric 20_M and (c) the anti-symmetric 4 of SU(4).

20_s contains the decuplet and 20_M have the SU(3) octet on the lowest layer, while the 4 has the SU(3) singlet at the bottom.

Heavy baryons

Singly heavy baryons

- Σ_c^{++}, Σ_c^{+}, Σ_c^{0}, Ξ_c^{+}, Ξ_c^{0}, Λ_c^{+}, Ω_c^{0} [Charm Sector]
  Z. Shah et al., EPJA 52, 313 (2016); CPC 40, 123102 (2016)
- Σ_b^{+}, Σ_b^{-}, Σ_b^{0}, Ξ_b^{+}, Ξ_b^{-}, Λ_b^{-}, Ω_b^{-} [Bottom Sector]
  Nucl. Phys. A 965,57 (2017); Few Body Syst. 59, 112 (2018)

Doubly heavy Baryons

- Ω_{cc}^{+}, Ω_{bb}^{-} and Ω_{bc}^{0} Z. Shah et al., Eur. Phys. J. C, **76**, 530 (2016).
- Ξ_{cc}^{+}, Ξ_{bb}^{-}, Ξ_{bc}^{0}, Ξ_{cc}^{++}, Ξ_{bb}^{0} and Ξ_{bc}^{+}
  Z. Shah et al., Eur. Phys. J. C, **77**, 129 (2017)

Triply heavy Baryons

- Ω_{ccc}, Ω_{bbb}, Ω_{bbc}, Ω_{ccb}
  Z. Shah et al., EPJA, **53**, 195 (2017); Few-Body Syst. 59, 76 (2018); CPC 42, 053101 (2018)

- The two heavy quark combinations cc, bb and bc unifies with s quark in case of three doubly heavy Ω baryons.
- Strangeness S= -1 and Isospin I= 0.
- While for six doubly heavy Ξ baryons light quarks u or d are combined with heavy quarks. The mass difference between the light quarks (u and d) is 12 MeV in our model. So, it is obvious that when we move toward the calculations of the excited states the baryon masses would also have a very small mass difference.
- For the sake of completeness we calculated whole mass spectrum for all six doubly heavy baryon: Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ξ_{bb}^{-}, Ξ_{bb}^{0}, Ξ_{bc}^{0} and Ξ_{bc}^{+} and noticed that it hardly differs less than $\approx$10 MeV
- The calculations have implemented for the ground state (1S), the radial excited states (2S -5S) and the orbital excited states (1P-5P, 1D-4D and 1F-2F).
- We consider all isospin splittings and accordingly J^P values are determined.

Ground states of Doubly heavy Ξ baryons

- SELEX experiment: a ground state at 3520 MeV containing two charm quarks and a down quark in its decay mode $\Xi_{cc}^{+} \to pD^{+}K^{-}$.
- the LHCb experiment: Ξ_{cc}^{++} with the mass (3621.40 $\pm$ 0.72 $\pm$ 0.27 $\pm$ 0.14) MeV and quark combination ccu. The decay mode of the experimental investigation is $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-}\pi^{+}\pi^{-}$.
- The ground and excited states of doubly heavy Ω baryons are experimentally unknown.

Baryons	Ξ_{bb}		Ξ_{bc}	
J^P	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{1}{2}^+$	$\frac{3}{2}^+$
Our work	10.317	10.340	6.920	6.986
Ref.[1]	10.093	10.133	6.820	6.900
Ref.[2]	10.162	10.184	6.914	
Ref.[3]	10.197	10.136	6.919	6.986
Ref.[4]	10.130	10.144	6.792	6.827
Ref.[5]	10.196	10.241	-	-
Ref. [6]	10.314	10.339	-	-
Ref. [7]	10.199	10.316	-	-
Ref. [8]	10.322	10.352	7.014	7.064
Ref. [9]	10.202	10.237	6.933	6.980

Mass Spectra: Radial Excited states

Baryon	State	J^P	A	B	[6]	[10]	[11]	[12]	[9]	[5]
Ω_{cc}	2S	$\frac{1}{2}^+$	4.028	4.041	4.227	4.180	4.112	4.268	4.075	4.050
		$\frac{3}{2}^+$	4.085	4.096	4.263	4.188	4.160	4.334	4.174	4.163
	3S	$\frac{1}{2}^+$	4.317	4.338	4.295			4.714	4.321	
		$\frac{3}{2}^+$	4.345	4.365	4.265			4.776		
	4S	$\frac{1}{2}^+$	4.570	4.598						
		$\frac{3}{2}^+$	4.586	4.614						
	5S	$\frac{1}{2}^+$	4.801	4.836						
		$\frac{3}{2}^+$	4.811	4.845						
Ω_{bb}	2S	$\frac{1}{2}^+$	10.730	10.736	10.707	10.693	10.604	10.830	10.610	
		$\frac{3}{2}^+$	10.737	10.743	10.723	10.721	10.622	10.839	10.645	
	3S	$\frac{1}{2}^+$	10.973	10.983	10.744			11.240	10.806	
		$\frac{3}{2}^+$	10.976	10.986	10.730			11.247	10.843	
	4S	$\frac{1}{2}^+$	11.191	11.205	10.994					
		$\frac{3}{2}^+$	11.193	11.207	11.031					
	5S	$\frac{1}{2}^+$	11.393	11.411						
		$\frac{3}{2}^+$	11.394	11.412						
Ω_{bc}	2S	$\frac{1}{2}^+$	7.473	7.480				7.559		
		$\frac{3}{2}^+$	7.490	7.497				7.571		
	3S	$\frac{1}{2}^+$	7.753	7.767				7.976		
		$\frac{3}{2}^+$	7.761	7.775				7.985		
	4S	$\frac{1}{2}^+$	8.004	8.023						
		$\frac{3}{2}^+$	8.009	8.028						
	5S	$\frac{1}{2}^+$	8.236	8.260						
		$\frac{3}{2}^+$	8.239	8.263						

Mass Spectra: Radial Excited states

Particle	State	J^P	A	B	A	B	[6]	[10]	[12]	[11]	[9]	[8]
	2S		3.912	3.925	3.905	3.920	4.079	4.029	4.183	3.976	3.910	4.030
	3S	$\frac{1}{2}^+$	4.212	4.233	4.230	4.159	4.206		4.640		4.154	
Ξ_{ccd}	4S		4.473	4.502	4.468	4.501						
and	5S		4.711	4.748	4.708	4.748						
Ξ_{ccu}	2S		3.976	3.988	3.970	3.983	4.114	4.042	4.282	4.025	4.027	4.078
	3S	$\frac{3}{2}^+$	4.244	4.264	4.238	4.261	4.131		4.719			
	4S		4.492	4.520	4.488	4.519						
	5S		4.724	4.759	4.720	4.759						
	2S		10.605	10.612	10.603	10.609	10.571	10.576	10.751	10.482	10.441	10.551
	3S	$\frac{1}{2}^+$	10.851	10.862	10.851	10.862	10.612		11.170		10.630	
Ξ_{bbd}	4S		11.073	11.088	11.075	11.090					10.812	
and	5S		11.278	11.297	11.282	11.301						
Ξ_{bbu}	2S		10.613	10.619	10.611	10.617	10.592	10.578	10.770	10.501	10.482	10.574
	3S	$\frac{3}{2}^+$	10.855	10.855	10.866	10.866	10.593		11.184		10.673	
	4S		11.075	11.090	11.077	11.092					10.856	
	5S		11.280	11.298	11.284	11.302						
	2S		7.236	7.244	7.231	7.240			7.478			7.321
	3S	$\frac{1}{2}^+$	7.495	7.509	7.492	7.507			7.904			
Ξ_{bcd}	4S		7.727	7.746	7.726	7.744						
and	5S		7.940	7.963	7.940	7.964						
Ξ_{bcu}	2S		7.260	7.267	7.256	7.263			7.495			7.353
	3S	$\frac{3}{2}^+$	7.507	7.521	7.505	7.518			7.917			
	4S		7.734	7.752	7.733	7.752						
	5S		7.944	7.968	7.945	7.969						

Orbital excited states of Ω_{cc} baryon

State	A	B	[6]	[10]	[13]	[9]	[7]	Others
$(1^2P_{1/2})$	3.964	3.989	4.086	4.046	4.061	4.002		4.009[11]
$(1^2P_{3/2})$	3.948	3.972	4.086	4.052	4.132	4.102	3.910	4.055[5]
$(1^4P_{5/2})$	3.935	3.958	4.220	4.152			4.058	
$(2^2P_{1/2})$	4.241	4.273	4.199	4.135		4.251		4.101[11]
$(2^2P_{3/2})$	4.228	4.259	4.201	4.140		4.345		
$(2^4P_{5/2})$	4.216	4.247						
$(3^2P_{1/2})$	4.492	4.529						
$(3^2P_{3/2})$	4.479	4.517						
$(3^4P_{5/2})$	4.469	4.506						
$(4^2P_{1/2})$	4.723	4.767						
$(4^2P_{3/2})$	4.712	4.755						
$(4^4P_{5/2})$	4.703	4.745						
$(1^4D_{3/2})$	4.141	4.170						4.233[5]
$(1^2D_{5/2})$	4.113	4.141	4.264	4.202			4.153	
$(2^4D_{3/2})$	4.395	4.432						
$(2^4D_{5/2})$	4.378	4.414	4.299	4.232				
$(3^4D_{3/2})$	4.432	4.631						
$(3^4D_{5/2})$	4.414	4.616	4.410					
$(1^2F_{7/2})$	4.264	4.296					4.383	
$(1^4F_{9/2})$	4.244	4.274					4.516	

Orbital excited states of Ω_{bb} baryon

State	A	B	[6]	[10]	[9]	[7]	Others
$(1^2P_{1/2})$	10.634	10.646	10.607	10.616	10.532		10.519[11]
$(1^2P_{3/2})$	10.629	10.641	10.608	10.619	10.566	10.593±58	10.520[14]
$(1^4P_{5/2})$	10.625	10.637	10.808	10.766	10.798	10.700±60	
$(2^2P_{1/2})$	10.881	10.897	10.796	10.763	10.738		10.683[11]
$(2^2P_{3/2})$	10.877	10.893	10.797	10.765	10.775		
$(2^4P_{5/2})$	10.874	10.888	11.028				
$(3^2P_{1/2})$	11.104	11.124	10.803		11.083		
$(3^2P_{3/2})$	11.101	11.120	10.805				
$(3^4P_{5/2})$	11.098	11.177	11.059				
$(4^2P_{1/2})$	11.310	11.332					
$(4^2P_{3/2})$	11.307	11.339					
$(4^4P_{5/2})$	11.305	11.322					
$(1^2D_{5/2})$	10.777	10.792	10.729	10.720			10.858±77
$(1^4D_{7/2})$	10.772	10.786					10.964±80
$(2^4D_{3/2})$	11.014	11.032					
$(2^2D_{5/2})$	11.008	11.025	10.744	10.734			
$(3^4D_{3/2})$	11.225	11.246					
$(3^2D_{5/2})$	11.219	11.240	10.937				
$(1^2F_{7/2})$	10.913	10.930					11.118±96
$(1^4F_{9/2})$	10.907	10.924					11.221±99
$(2^2F_{7/2})$	11.130	11.149					
$(2^4F_{9/2})$	11.125	11.144					

Orbital excited states of Ξ baryon

State	A Ξ^{+}_{cc}	B	A Ξ^{++}_{cc}	B	[6]	[10]	[11]	[9]	[7]	[1]	[8]	[13]	Others
$(1^2P_{1/2})$	3.853	3.865	3.846	3.861	3.947	3.910	3.880	3.838			4.073	3.892	3.853[5]
$(1^2P_{3/2})$	3.834	3.847	3.828	3.842	3.949	3.921		3.959	3.786	3.834	4.079	3.989	3.977[5]
$(1^4P_{5/2})$	3.818	3.890	3.871	3.888		4.163	4.092		4.155	3.949	4.047	4.089	
$(2^2P_{1/2})$	4.138	4.161	4.134	4.140	4.135	4.074	4.018	4.085					3.885[15]
$(2^2P_{3/2})$	4.121	4.144	4.118	4.140	4.137	4.078	4.197						4.017[15]
$(2^4P_{5/2})$	4.108	4.183	4.104	4.181	4.488								
$(3^2P_{1/2})$	4.395	4.426	4.393	4.409	4.149								
$(3^2P_{3/2})$	4.381	4.411	4.379	4.409	4.159								
$(3^4P_{5/2})$	4.369	4.399	4.412	4.396	4.534								
$(4^2P_{1/2})$	4.633	4.671	4.633	4.671									
$(4^2P_{3/2})$	4.620	4.658	4.620	4.657									
$(4^4P_{5/2})$	4.610	4.646	4.609	4.646									
$(1^4D_{5/2})$	4.011	4.033	4.006	4.029	4.027	4.052							
$(1^4D_{7/2})$	3.982	4.002	3.979	3.998	4.097			4.187	4.089	4.393			
$(2^2D_{5/2})$	4.270	4.299	4.267	4.297	4.164	4.091							
$(2^4D_{7/2})$	4.253	4.280	4.249	4.278	4.394								
$(3^4D_{3/2})$	4.541	4.578	4.539	4.578									
$(3^2D_{5/2})$	4.516	4.552	4.514	4.551	4.348								
$(1^4F_{7/2})$	4.194	4.225	4.154	4.182	4.267								
$(1^4F_{9/2})$	4.133	4.159	4.129	4.156	4.413								

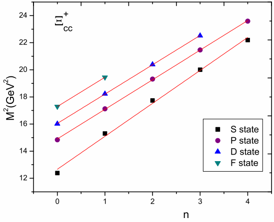
Orbital excited states of Ξ baryon

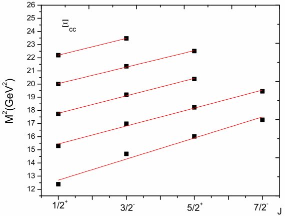
State	A Ξ_{bb}^{-}	B	A Ξ_{bb}^{0}	B	[6]	[10]	[11]	[9]	[7]	[8]	Others
$(1^2P_{1/2})$	10.507	10.514	10.504	10.511	10.476	10.493	10.406	10.368		10.691	10.405[5]
$(1^2P_{3/2})$	10.502	10.509	10.499	10.506	10.476	10.495		10.408	10.474	10.692	10.449[5]
$(1^4P_{5/2})$	10.514	10.521	10.512	10.518	10.759				10.588	10.695	
$(2^2P_{1/2})$	10.758	10.770	10.757	10.770	10.703	10.710	10.612	10.563			
$(2^2P_{3/2})$	10.754	10.766	10.753	10.765	10.704	10.713		10.607			
$(2^4P_{5/2})$	10.751	10.763	10.763	10.776	10.973	10.713					
$(3^2P_{1/2})$	10.985	11.001	10.986	11.002	10.740			10.744			
$(3^2P_{3/2})$	10.981	10.997	10.982	10.998	10.742			10.788			
$(3^4P_{5/2})$	10.978	10.994	10.991	11.007	11.004						
$(4^2P_{1/2})$	11.194	11.214	11.197	11.217				10.900			
$(4^2P_{1/2})$	11.191	11.210	11.194	11.213							
$(4^4P_{5/2})$	11.188	11.208	11.202	11.222							
$(1^2D_{5/2})$	10.652	10.663	10.650	10.661	10.592	10.676			10.742	11.002	
$(1^4D_{7/2})$	10.647	10.658	10.644	10.656		10.608			10.853	11.011	
$(2^4D_{5/2})$	10.888	10.903	10.888	10.903	10.613	10.712					
$(2^4D_{7/2})$	10.881	10.896	10.881	10.896		11.057					
$(3^4D_{5/2})$	11.103	11.122	11.105	11.124	10.809						
$(3^4D_{7/2})$	11.097	11.116	11.099	11.118							
$(1^4F_{7/2})$	10.792	10.806	10.789	10.803	11.004						
$(1^4F_{9/2})$	10.784	10.797	10.783	10.797	11.112						

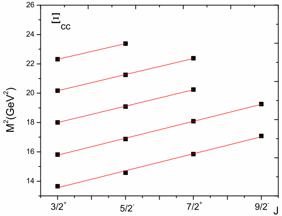
Regge Trajectories of Doubly heavy Ξ baryons

- Tullio Regge had introduced the topic of Regge trajectories to hadron physics in the 1960s [16, 17]. Further, it has been postulated that all strongly interecting particles must lie on Regge Trajectories called as Chew-Frautschi conjecture.
- Regge theory is a successful fundamental theory of strong interactions at very high energies and still an indispensable.
- One of the most distinctive features of Regge theory are the Regge trajectories. Regge trajectories are directly related with mass spectrum of hadrons.
- Using hadron masses, the trajectories can be generated in (n, M^2) and (J, M^2) planes.
- $n = \beta M^2 + \beta_0 \quad \& \quad J = \alpha M^2 + \alpha_0$
- Obtained masses are plotted in accordance with quantum number as well as with natural and unnatural parities.
- The important three properties of Regge Trajectories are: Linearity, Divergence and Parallelism.

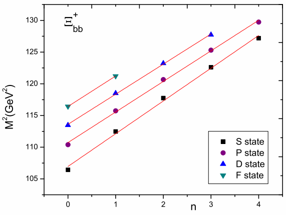
Regge Trajectories of Doubly heavy Ξ baryons

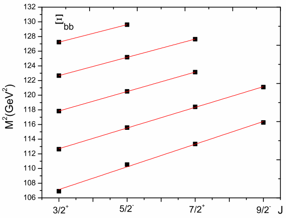


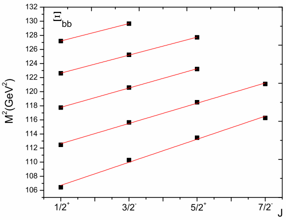




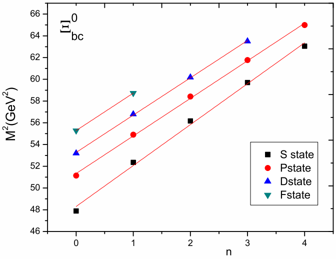
Regge Trajectories of Doubly heavy Ξ baryons

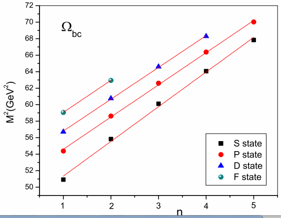




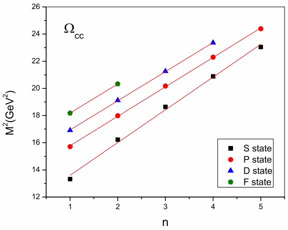


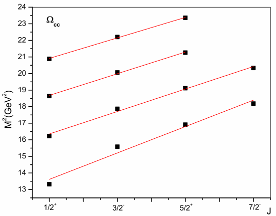
Regge Trajectories of Doubly heavy Ξ baryons

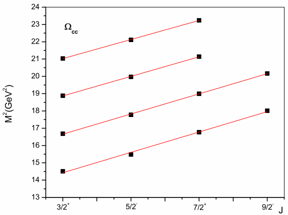




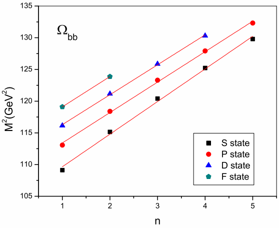
Regge Trajectories of Doubly heavy Ξ baryons

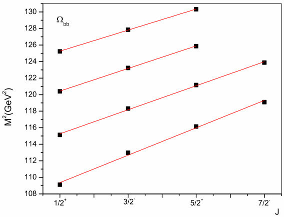


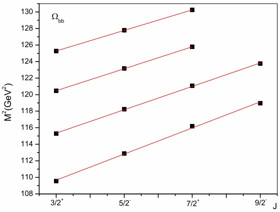




Regge Trajectories of Doubly heavy Ξ baryons







Magnetic moments

- The electromagnetic interactions are important to examine the inner structures of the heavy baryons.
- The magnetic moment of the particle is precisely depends on its structure and structure parameters so that it plays a crucial role in the study of structure of matter at the sub-nuclear level.
- The other theoretical analyses employ heavy baryon chiral perturbation theory [18], effective quark mass scheme [19], bag model [20, 21], light cone QCD sum rules [22], hypercentral model [23], Lattice QCD [24], Relativistic three quark model [25], relativistic quark model [26], chiral constituent quark model [27] and many more to calculate the magnetic moments.
- The study has been performed for all singly, doubly and triply heavy baryon systems for positive parity $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$.

Magnetic moments

The magnetic moment of baryons are obtained in terms of the spin, charge and effective mass of the bound quarks as[23, 28]

$$\mu_B = \sum_i \langle \phi_{sf} | \mu_{iz} | \phi_{sf} \rangle)$$

where

$$\mu_i = \frac{e_i \sigma_i}{2 m_i^{eff}} \tag{8}$$

The effective mass for each of the constituting quark m_i^{eff} can be defined as

$$m_i^{eff} = m_i \left(1 + \frac{\langle H \rangle}{\sum_i m_i} \right) \tag{9}$$

where, $\langle H \rangle = \mathrm{E} + \langle V_{spin} \rangle$.

Magnetic moments

Magnetic moments (in nuclear magnetons) with spin-flavour wavefunctions of $J^P = \frac{1}{2}^+$ heavy baryons.

Baryons	function	Our	[20]	[19]	[23]	[3]	[27]	[25]
Ξ_{cc}^{+}	$\frac{4}{3}\mu_c - \frac{1}{3}\mu_d$	0.784	0.722	0.800	0.860	0.785	0.850	0.72
Ξ_{cc}^{++}	$\frac{4}{3}\mu_c - \frac{1}{3}\mu_u$	0.031	0.114	-0.12	-0.137	-0.208	-0.150	
Ξ_{bb}^{-}	$\frac{4}{3}\mu_b - \frac{1}{3}\mu_d$	0.196	0.086	0.215	0.190	0.251		0.18
Ξ_{bb}^{0}	$\frac{4}{3}\mu_b - \frac{1}{3}\mu_u$	-0.662	-0.432	-0.630	-0.657	-0.742	-0.53	
Ξ_{bc}^{0}	$\frac{2}{3}\mu_b + \frac{2}{3}\mu_c - \frac{1}{3}\mu_d$	0.527	0.068	0.480	0.477	0.518		
Ξ_{bc}^{+}	$\frac{2}{3}\mu_b + \frac{2}{3}\mu_c - \frac{1}{3}\mu_u$	-0.304	1.093	1.718	-0.400	1.990		1.52
Ω_{cc}^{+}	$\frac{4}{3}\mu_c - \frac{1}{3}\mu_s$	0.692	0.668	0.690		0.635	0.730	0.67
Ω_{bb}^{-}	$\frac{4}{3}\mu_b - \frac{1}{3}\mu_s$	0.108	0.043	0.138	0.109	0.101		
Ω_{bc}^{0}	$\frac{2}{3}\mu_b + \frac{2}{3}\mu_c - \frac{1}{3}\mu_s$	0.439	0.034	0.407	0.397	0.368	0.45	

Magnetic moments

Magnetic moments (in nuclear magnetons) with spin-flavour wavefunctions of $J^P = \frac{3}{2}^+$ heavy baryons.

Baryons	function	Our	[20]	[19]	[23]	[3]	[27]	[29]
Ξ_{cc}^{*+}	$2\ \mu_c + \mu_d$	0.068	0.163	0.035	-0.168	-0.331	-0.220	
Ξ_{cc}^{*++}	$2\ \mu_c + \mu_u$	2.218	2.001	2.520	2.755	2.67	2.780	2.94
Ξ_{bb}^{*-}	$2\ \mu_b + \mu_d$	-1.737	-0.652	-1.029	-0.952	-1.110		-1.39
Ξ_{bb}^{*0}	$2\ \mu_b + \mu_u$	1.6071	0.916	1.507	1.577	1.870		2.30
Ξ_{bc}^{*0}	$\mu_b + \mu_c + \mu_d$	-0.448	-0.257	-0.551	-0.568	-0.712	-0.96	
Ξ_{bc}^{*+}	$\mu_b + \mu_c + \mu_u$	2.107	1.414	2.022	2.052	2.270		2.63
Ω_{cc}^{+}	$2\ \mu_c + \mu_s$	0.285	0.332	0.210	0.121	0.139	0.130	
Ω_{bb}^{*-}	$2\ \mu_b + \mu_s$	-1.239	-0.730	-0.805	-0.711	-0.662		-1.56
Ω_{bc}^{*0}	$\mu_b + \mu_c + \mu_s$	-0.181	-0.111	-0.309	-0.317	-0.261		

Light baryons

- Nucleons: neutron(n) and proton(p) and Δ resonances
- Hyperons: Λ, Σ, Ξ, Ω

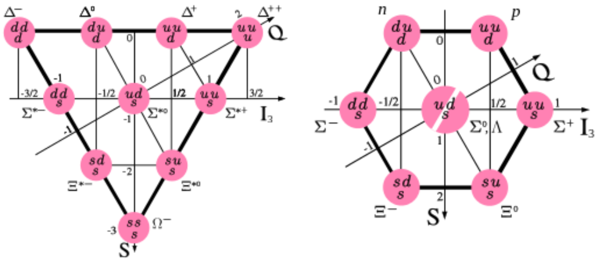
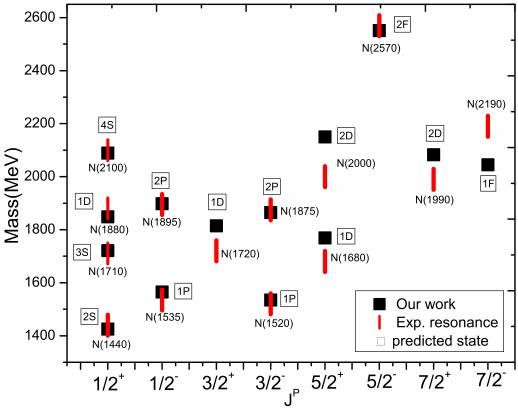


Figure: The symmetric decuplet 10 (left) and mixed symmetric octet 8 (right) of SU(3).

Light Baryon Spectrum



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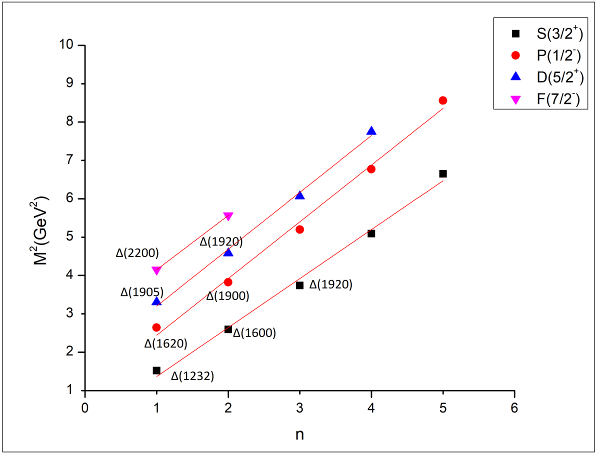
Light Baryon Spectrum



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Closure

- The baryons containing two heavy quarks; charm-charm, bottom-bottom and charm-bottom with a light strange quark are reviewed.
- The mass spectra for the excited states of all heavy flavored baryons and light $N*$ baryon are determined using hCQM.
- The regge trajectories are useful to determine the unknown states. Thus, we plot graphs in baryon spectra as well as in meson spectra.
- This study will definitely help future experiments and other theoretical models to identify the baryonic states from resonances
- Looking for the new results from future experiments.

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